ENERGY AND SEISMIC RETROFIT OF HISTORIC TIMBER-FRAMED HOUSES IN PORTUGAL: BUILDING PREDICTIVE MODELS IN FUTURE SCENARIOS

Stellacci, Stefania[1]*; Domingos, Leonor[2]*; Poletti, Elisa[3]**

[1] Stefania_Stellacci@iscte-iul.pt; [2]Leonor_Domingos@iscte-iul.pt; [3]*elisapoletti@gmail.com*
** University Institute of Lisbon (ISCTE-IUL), ISTAR, Lisbon, Portugal*
*** University of Minho, Department of Civil Engineering, ISISE, Guimarães, Portugal*

Keywords: Integrated analysis model, Timber-framed house, Climate change, Building simulation, Computational tools

Abstract:

This research addresses the comparison of building performance before and after implementing energy and seismic retrofitting techniques within simulation models, under the current climate condition vs. predicted environment conditions (2030-2100).

It aims to identify a set of feasible interventions within distinct indoor building conditions (number of inhabitants and occupancy schedule) in three design scenarios. To this end, we adopt parametric modelling tools (Rhinoceros, Grasshopper, EnergyPlus) combined with a multicriteria decision analysis (M-MACBETH, Measuring Attractiveness through a Categorical-Based Evaluation Technique).

This model is tested in an historic house, a multi-storey overhanging timber-framed house in Lisbon parish, which is representative of valuable traditional construction systems in high seismic hazard zone in the Mediterranean basin.

Future studies can address other building simulations evaluated against architectural, structural, environmental, and economic-related parameters. The influence of weighting on the interventions against different criteria can be addressed also considering the uncertainty about the impact of each group of intervention in sensitivity and robustness analyses.

1 INTRODUCTION

The use of advanced computer aids and digital simulations in Architecture, Engineering and Construction (AEC) has increased significantly in the last few years, especially in response to the global concerns related to climate change impacts [1, 2].

Large-scale projections emphasize the relevance of retrofitting the existing building stock for contributing to reach carbon-net emission by 2050 [3]. However, when an intervention is required in an existing building, AEC professionals are facing more challenges compared to those encountered in new building construction [4]. Existing buildings are then upgraded at low rate, given the low knowledge of the economic benefit of retrofitting, the need to involve several stakeholders throughout design, implementation, and maintenance phases, the complexity of the problem arising from building aging and decay patterns [5].

To identify the energy response and cost savings of retrofitted or new buildings, several performance simulation tools are on the market, among which the most common used by engineers, architects, builders, or HAVC (Heating, ventilation, and air conditioning) companies are *Energy Plus*, *DesignBuilder*, and *OpenStudio* for Building Energy Modelling (BEM). *Energy Plus* is a free software that includes Solar gain and daylighting calculation and Life Cycle Cost Analysis (LCCA)[6]. BEM combines the inputs of local weather and calculates thermal loads, system response, and energy use. Beside cost-related and occupant comfort parameters, the selection of the most suitable retrofitting solutions depends on other values and priorities, such as cultural and environmental factors. To evaluate a set of design solutions against different an often-conflicting criteria, multiple-criteria decision analysis tools (MCDA) can be also used to elicit specific retrofitting technique which reach a high performance in the simulated model [7, 8].

The present study extends the scope of previous research on the decision-making process in historic building based on context-based approach using a MCDA tool, MACBETH (*Measuring Attractiveness through a Categorical-Based Evaluation Technique*) [9, 10, 11, 12]. In this work, the analysis of energy retrofitting techniques is addressed together with seismic retrofitting techniques, projecting interventions toward a future-directed building management in accordance with European strategies [13].

In the first section of this article, we describe the methodological background, the research phases and the tools applied to simulate and automatically establish the building performance.

Then, we provide a brief overview of potential energy and seismic retrofitting techniques applied to a specific building typology (traditional timber-framed construction) followed by a selection of a combination of energy and seismic retrofitting techniques simulated in three scenarios. We perform the building simulation models comparing the current configuration in 2023 (baseline) *vs*. integrated retrofitting techniques in 2100, utilizing the parameters defined for climate projections. As indicated in the IPCC report 2023 (UN Intergovernmental Panel on Climate Change) there is more than 50% chance that global temperatures will reach or surpass 1.5 ºC between 2021 and 2040 across studied scenarios that consider the concentrations of greenhouse gases, aerosols, and other factors affecting the earth's climate system [14]. This conclusion is more dramatic than what was predicted in the previous years. For instance, the expected climate scenario in Portugal in 2100 can be more extreme than what was previously predicted. This research considers climate models about the number of hot days per year, ranging a maximum temperature of above 35 ºC between 1961 and 1990, and simulated scenarios until 2081-2100 [15].

Finally, a brief outlook of limitations and future perspectives of building simulation analysis is detailed.

2 METHODOLOGICAL BACKGROUND

2.1 Tools and datasets

To test the impact and compare the benefits of a set of retrofitting technique under future (expected) environmental conditions, we use a set of parametric advanced modelling tools: *Rhinoceros*, *Grasshopper*, and *EnergyPlus*.

Rhinoceros is a 3D modelling software, based on non-uniform rational B-splines (NURBS), where model geometry, materiality, constructions of a building (or built environment) can be modelled in accurate form. *Grasshopper* is a node-based algorithmic editing plug-in for *Rhinoceros*. It supports several plug-ins for addressing energy, thermal, and environmental analyses. In this study two plugins, *LadyBug* and *HoneyBee*, are chosen for their effectiveness proven in literature [16]. Designers can enter data on weather by means of *LadyBug* to visualize and analyse the response of the building. The weather data come from the American Department of Energy [17]. These findings can then be processed by turning simulation outputs into visual graphics. *Honeybee* enables to define detailed daylighting and thermodynamic modelling. Both *LadyBug* and *HoneyBee* run their digital simulations using *EnergyPlus* simulation engine. Being originated from various locations around the globe and spawning for several years, the weather dataset is exhaustive. This dataset enables designer to run accurate simulations and produce workable findings. Additionally, *HoneyBee* enables to add materials (either from the *EnergyPlus* database or *ad hoc* created), occupancy schedules for buildings, and loads (energy requirements) to *Rhinoceros* 3D model. Using the *EnergyPlus* weather files, it is possible to accurately define the location of the case study (country and city) as well as the direction regarding the four cardinal points, and impacts of natural light in the building performance or occupancy conditions.

The simulation model discussed in this study regards the building performance before and after implementing a set of energy retrofitting techniques applied to retrofitted load and non-load bearing components, under three scenarios of use. The weight of each criterion is defined through the pairwise comparison judgments using seven semantic categories defined in M-MACBETH [12].

2.2 Evaluation criteria

As unanimously acknowledged by heritage practitioners, researchers, and heritage agencies (among others), the historic built environment is a multi-dimensional, multi-attribute and multi-value setting [18].

The selection of the most suitable and effective intervention in a single historic building (or in a building stock) should be addressed considering a system of multi-dimensional values, yet this complexity is often overlooked in the current practice. Any interventions in built heritage planned for preservation, reuse, or strengthening purposes should include thorough analyses based on multiple evaluation criteria embracing: i) architectural/cultural parameters (material permanence, spatial configuration, visual and tactile appearance, and net interior area); ii) environmental-related parameters (free-floating internal temperature, weight carbon footprint, energy consumption, moisture safety); and iii) structural-related parameters (e.g. increase in strength or ductility); iv) cost-effectiveness (cost of raw materials, operational feasibility, and maintenance costs).

Table 1 shows the overview of a set of evaluation criteria and their performance evaluation levels, proposed by the authors of this research. These criteria differ for scope of application, since Material Permanence (MP), Weight Carbon Footprint (WCF), Energy consumption (EC), Moisture Safety (MS), Raw material cost and Operational feasibility, regard a single building sub-component (e.g. the timber-framed wall or the floor). Other criteria regard the whole building. The bases for comparison are qualitative performance levels, except to Weight carbon footprint, Energy consumption (EC), Raw material cost (RMC), and Installation/Maintenance cost (IMC), whose performance levels are quantitative.

Table 1: Overview of evaluation criteria, indicators, performance levels (compiled by the authors).

PARAMETERS	EVALUATION CRITERION	DESCRIPTION	PERFORMANCE EVALUATION LEVEL
Architectural	Material Permanence (MP)	Regards the intrusiveness of the intervention and the possible material variation of the authenticity of the original components. It is inversely proportional to the volume of the material to be removed [9]	**High (H):** Negligible replacement of original components. **Moderate (M):** Limited replacement of original components. **Low (L):** Significant replacement of original components. **Very Low (VL):** Complete replacement of original components.
	Spatial Configuration (SP)	Difference of the spatial configuration before and after the intervention	**High (H):** The main spatial features are similar to the original configuration. **Moderate (M):** The spatial features slightly differ to the original configuration. **Low (L):** Ceiling height and size of the room differ to the original spatial configuration. **Very Low (VL):** Relevant differences in height, size, lightening conditions compared to the original spatial configuration.
	Visual and Tactile Appeareance (VTA)	Aesthetic compatibility of the intervention [9]	**High (H):** Visual and tactile features are similar to the original. **Moderate (M):** The tactile consistency is different. **Low (L):** Increase of thickness, differences in tactile and material consistency. **Very Low (VL):** Relevant differences in thickness and in tactile, material, and colour consistency.
	Net Internal Area (NIA)	Decrease of the usable area within a building measured to the internal face of the perimeter walls at each floor level [11].	**High (H):** Decrease of 80-60% of the NIA of the original building, before the intervention. **Moderate (M):** Decrease of 60-40% of the original building, before the intervention. **Low (L):** 40-10% of the NIA of the original building, before the intervention. **Very Low (VL):** <10% of the NIA of the original building, before the intervention.
Environmental	Free-floating internal temperature variation (FIT)	Variation of the interior temperature (lowest, highest and average) during the simulation period. Might or not be comfortable for humans.	**High (H):** Thermal comfort of inhabitants is fully satisfied. Indoor temperatures are above 18-20º C in Winter and below 22º-26º C in Summer. **Moderate (M):** Thermal comfort of inhabitants is comfortable. Indoor temperatures are between 18-20º C in Winter or 22º-26º C in Summer, ensuring thermal comfort. **Low (L)**: Thermal comfort of inhabitants is unsatisfactory. Temperatures are below 18º C in Winter and above 26º C in Summer.
	Weight carbon footprint (WCF)	Embodied carbon per extra kg of material used in construction.	The lowest value of embodied carbon should be considered the **BEST** option, and the highest value of embodied carbon should be considered the **WORST** option.
	Energy consumption (EC)	Total energy in kWh necessary to keep the interior of the building comfortable for humans (between 18º-20º C in Winter and 22º-26º C in Summer), during the simulation period.	The lowest value of necessary energy are the **BEST** option, and the highest value of necessary energy are considered the **WORST** option.
	Moisture safety (MS)	Indoor moisture levels to protect occupants from adverse health effect	**High (H):** Humidity is between 30 to 60%. **Moderate (M):** Up to 70% humidity. **Low (L):** Above 70% to 100%.
Structural	Degree of improvement in mechanical behaviour in terms of resistance, ductility, and energy dissipation [10].		**Good (G):** Effectiveness in reduction of severe building damage and life-safety risks Significant improvement in mechanical behaviour (i.e. ductility, resistance) by minimizing the post-elastic movements of cracked adobe **Moderate (M):** Effectiveness in reduction of damage during moderate to severe events by minimizing the post-elastic movements of cracked adobe blocks. **Poor (P):** Low effectiveness of seismic damage mitigation or inappropriate to the building condition. **Very Poor (VP):** No significant improvement in mechanical behaviour or even worsening of seismic response
Cost-effectiviness	Raw material cost (RMC)	Direct and indirect cost of raw materials and components	The lowest cost value of raw material is considered the **BEST option**, and the highest value is the **WORST** option.
	Operational feasibility (OF)	Skilled labour requirement required to implement the intervention, transportation infrastructure, duration of works	**High (H):** Easy installation. **Moderate (M):** Installation may require specialised infrastructure or additional costs. **Low (L):** Specialised personnel
	Installation/Maintenance cost (IMC)	Maintenance period	**BEST** option: Non-specialised personnel and low-expensive maintenance cycle. **WORST** option: When specialised personnel and high-cost materials are required to maintain the retrofitted building/components.

3 ENERGY AND SEISMIC RETROFITTING TECHNIQUES

Distinct energy and seismic retrofitting techniques can be applied to the construction typology under analysis to improve occupant comfort and minimize potential impacts of earthquake, as discussed in literature. Non-exhaustive lists of potential retrofitting techniques are summarized in *Table 2* and *Table 3*, based on the literature and the current practice.

Table 2: Overview of energy retrofitting techniques in historic timber-framed buildings (compiled by the authors).

Building sub-components		Energy retrofitting (ER)	Parameters of energy retrofitting materials					
Load-bearing components	VERTICAL STRUCTURE		Thickness [mm]	Thermal Conductivity or U-value [W/(m2·K)]	Density [kg/m3]	Specific Heat Capacity [J/Kg-K]	Absorptance [0-1]	Radiance [0-1]
	External walls (masonry or brick wall, and timber frame wall)	**Mw0:** Existing multi leaves stone-masonry wall (groundfloor and party wall at all levels)	800	1,3	2750	2750	0,9	0,7
		ER_Mw1: Addition of rockwool panel at the internal side	25	0,035	45	1030	0,9	0,7
		ER_Mw2: Addition of cork panel at the internal side	40	0,042	120	1750	0,9	0,7
		Tfe0: Existing timer frame wall (above the ground floor and gable wall)	200	1,648	1905	839	0,9	0,7
		ER_Tfe1: Addition of wood-fibre boards at the internal side	90	0,038	50	2100	0,9	0,7
		ER_Tfe2: Addition of cork panel at the internal side	40	0,042	120	1750	0,9	0,7
		ER_Tfe3: Internal cavity, addition of polyurethane and plasteboard	105	0,023	30	1400	0,9	0,7
		ER_Tfe4: Installation of hemp-fibre insulation boards (90% hemp fiber and 10% polymer binder) as infill panels at the internal side	50	0,04	26	1600	0,9	0,7
		ER_Tfe5: PIR (polyisocyanurate) insulation board and gypsum plasteboard infill at the internal side	40	0,022	30	1400	0,9	0,7
		ER_Tfe6: Cellulose fiber projection at the internal side	100	0,04	1592	1300	0,9	0,7
	HORIZONTAL AND ROOF STRUCTURES							
	Timber floor made of floorboards laid across timber joists	**Tfi0:** Existing timber floor (above the groundfloor)	250	0,200	500	2300	0,9	0,7
		ER_Tfl1: Addition of rockwool panel between floor joists, vapour permeable membrane	40	0,035	45	1030	0,9	0,7
		ER_Tfl2: Addition of rockwool panel between floor joists and wood-fibre board tongue, groove boards fixed below floor jo	40					
		ER_Tfl3: From above the floor using hemp-fibre insulation boards	50	0,039	30	1600	0,9	0,7
		ER_Tfl4: From above the floor, floorboards lifted and replaced and air and vapour control layer						
		ER_Tfl5: From above the floor, floorboards lifted and replaced and air and vapour control layer e below plywood boarding to support insulation						
	Roof and dormer windows	**Ro0:** Exsting roof	10	1,7	2605	325	0,9	0,7
		ER_Ro1: Addition o fmineral fibre board to the roof surface from above the top floor ceiling between the ceiling joists	19.5	0,036	300	1440	0,9	0,7
		ER_Ro2: Adding an insulation board (wool of sheep or compressed hemp) to the roof surface from above the top floor ceiling between the ceiling joists using	100	0,035	45	1030	0,9	0,7
		ER_Ro3: Expanded polyisocyanurate / PIR (Celotex or Kingspan)	17.5	0,022	30	1400	0,9	0,7
		ER_Ro4: Plasterboard space blanket (fibreglass wrapped in space blanket)	27	0,015	150	1000	0,9	0,7
Non-load bearing components	WINDOWS		Thickness [mm]		Thermal transmittance or U-value [W/m2-K]		Solar Heat Gain Coefficient [%]	Visible Light Transmittance [%]
	W0: Existing window		6		1,02		82	88
	ER_W2: Timber frame, triple glazing. Window replacement with low-E glass window high-performance in summer		6 + 12 (Ar) + 4 + 12 (Ar) + 4		0.70		18	27
	ER_W3: Timber frame, triple glazing. Window replacement with low-E glass window high-performance in summer		6 + 12(Ar) + 6 + 12(Ar) + 6		0.68		50	68
	LIGHTING SYSTEM							
	ER_LS1: Replacement of incandescent lamps (40W) for LED lamps (9W)		-		-		-	-
	ER_LS2: Replacement of incandescent lamps (60W) for LED lamps (13W)		-		-		-	-

Energy planning, technical risks, and relevant issues (e.g. breathing performance) related to energy retrofitting of external walls in stone (at ground floor, rear façade, party walls) and in timber-framed (upper floors of the main façade and internal walls) are indicated in literature, especially in historic timber-framed buildings in England [19](*Table 2*).

Regarding this type of historic construction, studies on techniques to restore or reinforce walls, horizontal structures, and their connections are more extensive and systematized, especially in seismic-prone areas where this traditional construction was commonly employed. In simulated environments or in laboratory companies, different techniques are analysed to understand the potential improvement of structural performance, in terms of resistance, stiffness, strength, ductility, and energy dissipation for each type of damage scenario [e.g. 9, 20, 21, 22, 24].

This set of seismic retrofitting techniques are identified for each building sub-component (vertical and horizontal structures, and roof), that include both natural-based building solutions, steel and concrete composite solutions.

The connections between horizontal and vertical structures (e.g. horizontal steel bars anchored to steel plates, horizontal confining reinforced concrete elements, insertion of corner triangular stone elements and injecting of walls, or addition of steel ribbons and injection) are not included in this analysis, although its importance has been stressed by several authors [24].

This study focuses on a set of reinforced technique, indicated in grey-coloured cells in *Table 3*.

Table 3: Overview of seismic retrofitting techniques in historic timber-framed buildings (compiled by the authors).

Historic building sub-components (Local denomination)		**Seismic retrofitting (SR)**
VERTICAL STRUCTURE		
EXTERNAL WALLS	multi leaves stone-masonry wall with lime mortar (parede em alvenaria de pedra)	**SR_Mw1:** Deep re-pointing on mortar joints
		SR_Mw2: Lime-based grouts into the hollow middle part of the wall
		SR_Mw3: Cement-silicate injection into the hollow middle part of the wall with moderate pressure (up to 2
		SR_Mw4: Polymer-based injection into the hollow middle part of the wall
		SR_Mw5: Reinforced coating mortar with electrowelded steel meshes (extended metal mesh and reduced diameter bars)
		SR_Mw6: Reinforced concrete jackets enclosed and anchored to old wall (5-10cm)
		SR_Mw7: Transversal metal ties (treated bars)
		SR_Mw8: Addition of vertical steel prestressed cables
		SR_Mw9: Addition of plastic ribbons or textile bands made of GFRP (Glass Fiber Reinforced Polymer)
		SR_Mw10: Addition of plastic ribbons or textile bands made of CFRP (Carbon Fiber Reinforced Polymer)
		SR_Mw11: Seismic isolation bearings and dampers
	half-timbered frame wall (frontal tecido)	**SR_Tfe1:** Substitution of local decayed timber elements with autoclaved timber components + Partial removal of infill and repair of the brick or rubble masonry + Strengthening carpentry joints using stainless steel plates with bolts + Mono or multi-layer plaster by using NHL- based and/or lime-based render
		SR_Tfe2: Substitution of local decayed timber elements with autoclaved timber components + Replacement of infill using clay bricks (or roof tiles) and hydraulic lime mortar + Strengthening carpentry joints using stainless steel screws+ Mono or multi-layer plaster by using NHL- based and/or lime-based
		SR_Tfe3: Substitution of local decayed timber elements with autoclaved timber components + Replacement of infill using clay bricks (or roof tiles) and hydraulic lime mortar + Strengthening carpentry joints using NSM (steel bars or FRP bars)+ Mono or multi-layer plaster by using NHL- based and/or lime-based render reinforced by fiberglass mesh
INTERNAL WALLS	thin wattleand-daub walls (tabique)	**SR_Tfi1:** Reinforcement with timber components
		SR_Tfi2: St. Andrew steel cross + steel plates, one placed horizontally, along the entire length of the wall, and another vertically, spanning its entire height
		SR_Tfi3: Metalic sheet
HORIZONTAL STRUCTURE		
TIMBER FLOOR		**SR_fl1:** New planks connected to existing beams by means of dry hardwood pins
		SR_Tfl2: Addition of a second layer of wood planks (30mm thick) arranged crosswise on the existing one and fixed with steel screws
		SR_Tfl3: Diagonal bracing of the existing wood planks by light gauge steel plates
		SR_Tfl4: Diagonal bracing of the existing wood planks by FRP laminae
		SR_Tfl5: Three layers of plywood panels glued on the existing wood planks
		SR_Tfl6: Cross-laminated timber panels and tempered glass strips
		SR_Tfl7: Reinforced concrete slab connected by means of studs

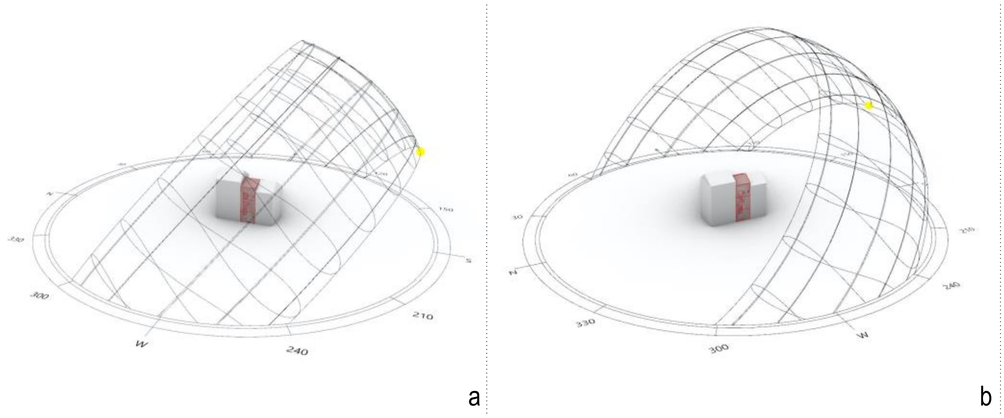
3.1 Case study

The case study is selected for its main relevant cultural features (traditional timber-framed system), relevant details (such as the curved timber doorjamb) [24], its location (Lisbon), and in the expected climate scenario discussed by Soares et al. (2019), among others [26]. Characterized by high or very high index of extreme precipitation susceptibility (EPSI), the Lisbon metropolitan area is particularly vulnerable to the impact of climate change, for its location in the mouth of the river Tagus.

This double-jetted dwelling is located in *Rua do Benformoso* n.101-103, with the rear façade, facing *Beco da Oliveira*. The still-standing house is one third of the original block, with shop on the ground floor and a housing on the upper floors. The date of construction is uncertain, but its main architecture features recall the vernacular architecture of the mid-16th-17th century. Approved by municipality, two-thirds of the original block were demolished in 1928 (AML, Dossier no. 33695). The exterior walls are stone masonry on the ground floor, timber frame walls filled by rubble stone on the upper, floors are wooden joists and boards. The structural and the architectural features of the still standing building present a high degree of authenticity [25].

Figure 1 shows the low light exposure of the building that is modelled in *Rhinoceros* and then imported to *Grasshopper*. This chart represents the path the sun takes over the year, in Lisbon, rendered using *LadyBug*.

Figure 1: Sun path diagram generated by *LadyBug*, 1st January, 0h00: a) main facade; b) rear façade (by Leonor Domingos).



3.2 Simulation modelling: scenarios and energy building performance

Considering the current configuration, the spatial constraints, and potential uses of this building, we define three scenarios. *Table 4* shows the indoor building conditions, depending on the number of inhabitants, equipment, and temperature parameters, with the occupancy schedule over the year.

Table 4: Indoor building conditions (number of inhabitants and occupancy schedule) in three scenarios.

	No.of inhabitants	Use	Lightning density per area	Ventilation rate per person	Equipment load per area	Infiltration rate per area of facade
Scenario 1	6	groundfloor: shop; 1st, 2nd floors : house: 3rd floor: office	15 W/m2 incandescent lamps	0,008 m3/s per person	5 W/m2 (1 laptop + 1 TV)	0,0006 m3/s/m2 (leaky building)
Scenario 2	3	groundfloor: shop; 1st, 2nd, 3rd floors: house	3 W/m2 per LED lampade		2 W/m2 (1 laptop)	0,0001 m3/s/m2 (tight building)
Scenario 3	4	groundfloor, 1st, 2nd floors : house: 3rd floor: office	15 W/m2 incandescent lamps		15 W/m2 (different equipments including 1 laptop + 1 TV)	

To conduct energy simulations, *Grasshopper* requires specific inputs, such as equipment, lightning, and ventilation loads, as well as the number of people inhabiting the building (floor area ratio). The lightning density per area depends on the type of lamps used (15 W/m^2 is usually indicated for incandescent lamps, which are less efficient in terms of energy, while 3 W/m^2 is indicated for LED lamps, which are the most efficient solution). The minimal ventilation rate per person is defined at 0,008 m^3, which is the minimum for guarantying a healthy indoor environment [27]. Regarding the equipment load, the value is defined depending on the number of electronic devices for a determined space/floor, 2 W/m^2 is the value considered for one laptop in a room, while 15 W/m^2 corresponds to an office. Finally, the values of infiltration rate per area of façade depends on the construction quality of the building in terms of tightness. The current historic building is a 'leaky building' (term defined within *Grasshopper*) due to the existing quality of construction system, while a building after retrofitting is considered as a 'tight building'.

The construction materials are defined within the simulated model using density, thermal conductivity, thickness, specific heath capacity, absorptance, and radiance. Each layer that constitutes the walls are modelled within the software environment, with the definition of the most outward and the most inward layer and the addition of construction elements. Other relevant inputs required for conducting the simulation are the occupancy schedule and the indoor temperature. In this study, we simulate 24-hours of occupation over 12 months of the year, and a comfort indoor temperature ranging from 19º C to 25º C [28]. The combination of energy intervention (*Table 5*) is defined for homogeneous raw materials. Such a homogeneous intervention would entail reasonable economic and practical feasibility, i.e. minimum number of material types and skills required in the work site. The energy performance of the whole buildings is evaluated for each set of retrofitting solutions within three design scenarios, considering different indoor building conditions.

Table 5: Simulated energy building performance of the case study

			Indoor environment		Energy consumption*				
Scenario (see Table 4)		**Simulated energy building performance**	**Interior air temperature [º]**	**Humidity (max, min, avr) [%]**	**Annual Kwh spent for thermal comfort (19º-25º C) [Kwh]**	**Energy [Kwh/month]**	**Cost per year [€]**	**Cost per month [€]**	**Cost Reduction [%]**
no energy retrofitting	**Scenario 1**	**Mw0 + Tfe0 + Tfl0 + Ro0 + W0** (Year: 2023)	Max: 35,16º; Min: 10,72º; Avr: 22,47º	Max: 82,12%; Min: 21,80%; Avr: 49,68%	16198,13	1349,84	2429,72	202,48	0 (baseline)
		Mw0 + Tfe0 + Tfl0 + Ro0 + W0 (Year: 2100)	Max: 38,38º; Min: 12,81º; Avr: 24,06º	Max: 82,12%; Min: 24,40%; Avr: 48,53%	12682,93	1506,91	1902,44	158,54	21,7
energy retrofitting	**Scenario 2**	**Mw1+Tfe1+Tfl1+Ro1+W3**	Max : 36,77º; Min: 12,99º; Avr: 23,67º	Max: 77,15%; Min: 29,74%; Avr: 49,68%	4913,28	409,44	736,99	61,42	70
	Scenario 3		Max: 53,00º; Min: 20,57º; Avr: 35,07º	Max: 51,78%; Min: 12,43%; Avr: 26,86%	12325,09	1027,09	1848,76	154,06	24
	Scenario 2	**Mwe2 + Tfe2 + Tfl3 + Ro2 + W4 + LS1**	Max: 38,60º; Min: 14,20º; Avr: 25,42º	Max: 72,80%; Min: 21,12%; Avr: 45,01%	5432,67	452,72	814,9	67,9	66
	Scenario 3		Max: 52,12º; Min: 20,06º; Avr: 34,83º	Max: 52,83%; Min: 10,41%; Avr: 27,26%	7966,28	633,86	1194,94	99,58	51
energy retrofitting + seismic retrofitting	**Scenario 2**	**Mw1+Tfe1+Tfl1+Ro1+W3+ Mw3+Tfe1**	Max : 33,24º; Min: 15,13º; Avr: 23,63º	Max: 71,68%; Min: 36,07%; Avr: 49,58%	4367,53	363,96	655,13	54,59	73
	Scenario 3		Max : 46,62º; Min: 23,95º; Avr: 35 ,07º	Max: 41,32%; Min: 15,84%; Avr: 26,03%	5624,36	468,7	853,65	70,31	65

▨ Best energy saving solutions
*comfort requirements

The first simulation model is conducted to understand the building performance nowadays, with the current Lisbon weather, the current occupancy, use, and construction conditions of the building. The second simulation model differs for the climate condition, which are expected 100 years from now. As the climate will get warmer, the interior air temperature rises about 2º C, with humidity decreasing about 1%, in average. However, the temperature variating between 10/12º C minimum in winter, and 35/38º C maximum in summer, makes the interior building temperature very uncomfortable, and possibly even dangerous to human health. Considering these conditions, the energy consumption required to guarantee the indoor comfort levels is approximately 16.000,00 kWh per year, for the current building, and about 12.000,00 kWh in 2100. This may seem contradictory, but there are various reasons behind this energy demand reduction. As the temperature rises, less energy is required to warm the building during the winter, making heating in the winter almost unnecessary. Also, being a 'leaky building', the heat loss is expressive especially during the summer. Although temperatures will be much hotter during summer, there will likely be quite a large difference between the daytime and nighttime temperatures. This will cause the buildings to lose heat during the night, as they’re not insulated, regulating the average interior temperature of the building. The analysis is run for the whole year, considering winter and summer, probably if only summer was considered, it would be possible to see that the cooling loads would be much higher, as only about 3 months of the year would be considered, but considering the whole year, the energy needs decrease in a warmer climate.

The simulated building performance in Scenarios 1 and 2 foresee the use of rockwool and wood fiber boards, while in Scenario 3 the model includes cork and hemp fiber boards as energy retrofitting solutions. In both cases, the retrofitting solutions are less effective in Scenario 3, due to the use of incandescent lamps and a heavier equipment load. Comparing Scenarios 1 and 2 with Scenario 3, the first options are more energy efficient, with a cost reduction of 70% when considering more efficient lamps and low equipment load. When considering less efficient lamps and more equipment load, the energy retrofitting that include cork and hemp fiber boards are more efficient, with a cost reduction of 51%. Scenario 2 includes the most efficient energy retrofitting solutions and the more likely to be adopted, while Scenario 3 considers a very heavy equipment load and incandescent lamps that are environmentally unfriendly. In fact, the use of LED lamps is the most likely choice. In the last simulation model where energy and seismic retrofitting are integrated, the cost reduction of energy load is relevant, amounting to 73%.

In comparing the building performance of the case study under different scenarios, we stress that the integrated retrofitting techniques proposed to improve the comfort of the occupants over the year and guarantee to withstand effects of seismic forces are the best energy saving solutions (*Table 5*, grey coloured cells).

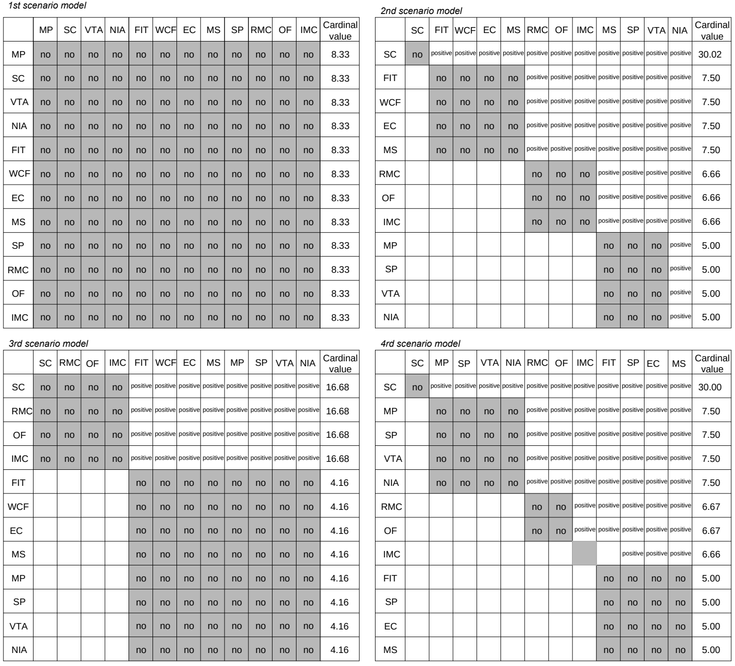
4 MULTICRITERIA DECISION ANALYSIS (MCDA)

MCDA is an umbrella term referring to the tools that support the decision-making processes based on computerized or human-powered approach. M-Macbeth is an interactive approach requiring only qualitative judgements about differences to help a decision maker or a decision advising group to quantify the relative attractiveness of options. It is based on qualitative (nonnumerical) pairwise comparison judgments [9, 12]. In this context, it is used to define the weight of the criteria and support to define distinct model scenarios. In future studies, a group of experts in built heritage, urban planning, and energy and seismic retrofitting can evaluate the techniques indicated in *Table 3* (or other in literature) against the evaluation criteria defined in *Table 2*. These inputs can be used to address a multicriteria decision analysis to elict the best solutions considering all inputs obtained from building simulation model.

We identify three design scenarios, the first with no dominating criteria, the second scenario where environmental and structural parameters are more important, the third scenario with cost-effectiveness as dominant criterion and the other criteria equally important. *Figure 2* shows the matrices built through pairwise comparison judgments and the thresholds, suggested by M-MACBETH, within which the consistency of these judgment is guaranteed.

The decision-maker (building owners and/or users) based on the state of conservation of the building and their constraints can use one of these scenario models. In this case, the decision-maker should select the scenario model in the medium-long term where the architectural and cultural values are equally important as the construction reliability of the building. If we retrofit the building for a long-term perspective, environmental parameters should be the most important.

Figure 2: Macbeth judgment matrices related to the difference of attractiveness between each criterion



1st scenario model

	MP	SC	VTA	NIA	FIT	WCF	EC	MS	SP	RMC	OF	IMC	Cardinal value
MP	no	no	no	no	no	no	no	no	no	no	no	no	8.33
SC	no	no	no	no	no	no	no	no	no	no	no	no	8.33
VTA	no	no	no	no	no	no	no	no	no	no	no	no	8.33
NIA	no	no	no	no	no	no	no	no	no	no	no	no	8.33
FIT	no	no	no	no	no	no	no	no	no	no	no	no	8.33
WCF	no	no	no	no	no	no	no	no	no	no	no	no	8.33
EC	no	no	no	no	no	no	no	no	no	no	no	no	8.33
MS	no	no	no	no	no	no	no	no	no	no	no	no	8.33
SP	no	no	no	no	no	no	no	no	no	no	no	no	8.33
RMC	no	no	no	no	no	no	no	no	no	no	no	no	8.33
OF	no	no	no	no	no	no	no	no	no	no	no	no	8.33
IMC	no	no	no	no	no	no	no	no	no	no	no	no	8.33

2nd scenario model

	SC	FIT	WCF	EC	MS	RMC	OF	IMC	MS	SP	VTA	NIA	Cardinal value
SC	no	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	30.02
FIT		no	no	no	no	positive	positive	positive	positive	positive	positive	positive	7.50
WCF		no	no	no	no	positive	positive	positive	positive	positive	positive	positive	7.50
EC		no	no	no	no	positive	positive	positive	positive	positive	positive	positive	7.50
MS		no	no	no	no	positive	positive	positive	positive	positive	positive	positive	7.50
RMC						no	no	no	positive	positive	positive	positive	6.66
OF						no	no	no	positive	positive	positive	positive	6.66
IMC						no	no	no	positive	positive	positive	positive	6.66
MP									no	no	no	positive	5.00
SP									no	no	no	positive	5.00
VTA									no	no	no	positive	5.00
NIA									no	no	no	positive	5.00

3rd scenario model

	SC	RMC	OF	IMC	FIT	WCF	EC	MS	MP	SP	VTA	NIA	Cardinal value
SC	no	no	no	no	positive	positive	positive	positive	positive	positive	positive	positive	16.68
RMC	no	no	no	no	positive	positive	positive	positive	positive	positive	positive	positive	16.68
OF	no	no	no	no	positive	positive	positive	positive	positive	positive	positive	positive	16.68
IMC	no	no	no	no	positive	positive	positive	positive	positive	positive	positive	positive	16.68
FIT					no	no	no	no	no	no	no	no	4.16
WCF					no	no	no	no	no	no	no	no	4.16
EC					no	no	no	no	no	no	no	no	4.16
MS					no	no	no	no	no	no	no	no	4.16
MP					no	no	no	no	no	no	no	no	4.16
SP					no	no	no	no	no	no	no	no	4.16
VTA					no	no	no	no	no	no	no	no	4.16
NIA					no	no	no	no	no	no	no	no	4.16

4rd scenario model

	SC	MP	SP	VTA	NIA	RMC	OF	IMC	FIT	SP	EC	MS	Cardinal value
SC	no	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	30.00
MP		no	no	no	no	positive	positive	positive	positive	positive	positive	positive	7.50
SP		no	no	no	no	positive	positive	positive	positive	positive	positive	positive	7.50
VTA		no	no	no	no	positive	positive	positive	positive	positive	positive	positive	7.50
NIA		no	no	no	no	positive	positive	positive	positive	positive	positive	positive	7.50
RMC						no	no	positive	positive	positive	positive	positive	6.67
OF						no	no	positive	positive	positive	positive	positive	6.67
IMC										positive	positive	positive	6.66
FIT									no	no	no	no	5.00
SP									no	no	no	no	5.00
EC									no	no	no	no	5.00
MS									no	no	no	no	5.00

Architectural parameters: **MP**: Material Permanence; **SC**: Spatial Configuration; **VTA**: Visual and Tactile Appearance; **NIA**: Net Interior Area. *Environmental parameters:* **FIT**: Free-floating Internal Temperature; **WCF**: Weight Carbon Footprint; **EC**: Energy Consumption; **MS**: Moisture Safety. *Structural parameters:* **SP**. *Cost-effectiviness*: **RMC**: Raw material cost; **OF**: Operational feasibility; **IMC**: Installation/Maintenance Costs

5. Limitations and future research perspectives

This research develops simulation models related to load-bearing and non-load bearing components, if the foundations do not require any interventions and focusing on few energy and seismic retrofitting techniques. A broad comparison can be addressed by simulating other retrofitted buildings and by defining different periods of occupancy or equipment loads. Additionally, to address more accurate energy simulation procedures, the baseline generally covers a period of thirty, ten or five years. As previously discussed [11], weather data is unavailable in the format required in the simulation process (.EPW file) within *Grasshopper* environment. The input data in the baseline is the average climatic data from *EnergyPlus* (2022)[6]. Local weather data (*EnergyPlus* Weather File) files are not available. Future research can investigate in more detail other simulations and identify the influence of weighting on the interventions against different criteria, the uncertainty about the impact of each group of intervention in sensitivity and robustness analyses.

6. Concluding remarks

This study aims to raise awareness on the importance of defining climate-sensitive design solutions integrated with seismic-resistant measures, while preserving the identity value of the built heritage beyond real estate market interests. The interventions implemented should reflect the preferences of the representatives of each decision-making group (e.g. inhabitants, heritage-professionals, real-estate agents), which should be involved throughout the problem structuring process and the design phases. To contribute to show how AEC professionals can leverage tools and software currently available, a comparative analysis of building performance is addressed within different scenarios. This study provides an overview of evaluation criteria that encompass multi-values and multi-dimensional aspects, a set of interventions techniques for energy and seismic retrofitting related to a relevant construction type in the Mediterranean basin.

AUTOR CONTRIBUTIONS

The first author defined the retrofitting techniques, criteria, and performance levels with the other authors. The second author addressed the simulation model and discussed the results. Relevant comments and suggestions were provided by the third author.

ACKNOWLEDGEMENTS

This work was partially supported by Fundação para a Ciência e a Tecnologia, I.P. (FCT) [ISTAR Projects: UIDB/04466/2020 and UIDP/04466/2020].

REFERENCES

[1] IPCC (2021), Climate Change 2021 the Physical Science Basis, IPCC, Geneva.

[2] IEA (2022), “Sustainable recovery”, The International Energy Agency, available at: http://www.iea. org/reports/sustainable-recovery

[3] Deb and Schlueter (2021). Review of data-driven energy modelling techniques for building retrofit, *Renewable and Sustainable Energy Reviews* (144), 110990. https://doi.org/10.1016/j.rser.2021.110990

[4] Ma Z, Cooper P, Daly D, Ledo L. Existing building retrofits: Methodology and state-of-the-art. Energy and buildings. 2012; 55:889-902. https://doi.org/10.1016/j.enbuild.2012.08.018

[5] Sanhudo et al. (2018), Building information modeling for energy retrofitting – A review, *Renewable and Sustainable Energy Reviews* (89), 249-260.

[6] EnergyPlus (2022), “Weather data sources”, available at: https://energyplus.net/weather/sources (accessed 12 May 2023).

[7] Caterino, N., Iervolino, I., Manfredi, G., and Cosenza, E., 2008. Multi-Criteria Decision Making for Seismic Retrofitting of RC Structures. *Journal of Earthquake Engineering*. 12 (4), pp. 555–583.

[8] Giuliani, F., De Falco, A., Landi, S., Giorgio Bevilacqua, M., Santini, L., and Pecori, S., 2018. Reusing grain silos from the 1930s in Italy. A multi-criteria decision analysis for the case of Arezzo. *Journal of Cultural Heritage*. 29, pp. 145–159.

[9] Stellacci, S., Rato, V., Poletti, E., Vasconcelos, G., and Borsoi, G., 2018. Multi-criteria analysis of rehabilitation techniques for traditional timber frame walls in pombalino buildings (Lisbon). *Journal of Building Engineering*. 16, pp. 184–198.

[10] Baquedano Juliá, P., Stellacci, S., and Poletti, E., 2022. Evaluation of retrofitting techniques for historical adobe constructions using a multi-criteria decision analysis: the Case Study of Chile. *International Journal of Architectural Heritage*.

[11] Stellacci, S., Domingos, L., and Resende, R., 2022. Integrated computational approaches for energy retrofit of historical buildings in extreme climate environments. *International journal of building pathology and adaptation*.

[12] Bana e Costa, C. (1994). MACBETH-An interactive path towards the construction of cardinal value functions. *International Transactions in Operational Research*, *1*(4). doi: 10.1016/0969-6016(94)90010-8

[13] RECAST (EPBD), 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). *Official Journal of the European Union*. 18 (6).

[14] IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 36 pages. (in press).

[15] Carvalho, A., Schmidt, L., Santos, F. D., & Delicado, A. (2014). Climate change research and policy in Portugal. WIREs Climate Change, 5(John Wiley & Sons), 199-217.

[16] Tedeschi, A. (2011), Parametric Architecture with Grasshopper, Le Penseur, Napoli.

[17] Department of Energy (2020), "Energy Plus", Office of Energy Efficiency and Renewable Energy. available at: https://www.energy.gov/eere/buildings/downloads/energyplus-0

[18] Mazzanti, M. (2002) Cultural heritage as multi-dimensional, multi-value and multi-attribute economic good: toward a new framework for economic analysis and valuation The Journal of Socio-Economics (31) 5, 529-558, https://doi.org/10.1016/S1053-5357(02)00133-6

[19] Historic England (2012) Energy Efficiency and Historic Buildings, Oxley Conservation. Available at: https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/

[20] Luso, E. & Lourenço, P.B. (2017) Experimental laboratory design of lime based grouts for masonry consolidation, *International Journal of Architectural Heritage*, (11)1143-1152.

[21] Cóias, Vítor. Reabilitação estrutural de edifícios antigos: alvenaria, madeira: técnicas pouco intrusivas. Argumentum, Lisboa, 2007.

[22] Parisi, M.A., Piazza, M. (2015) Seismic strengthening and seismic improvement of timber structures, Construction and Building Materials, Vol. 97, 55-66. https://doi.org/10.1016/j.conbuildmat.2015.05.093

[23] Gubana, A. (2015) State-of-the-Art Report on high reversible timber to timber strengthening interventions on wooden floors, Vol. 97, 25-33. https://doi.org/10.1016/j.conbuildmat.2015.06.035

[24] Tomasi, R., Crosatti, A., Piazza, M. (2010) Theoretical and experimental analysis of timber-to-timber joints connected with inclined screws, Construction and Building Materials, Vol. 24 (9),1560-1571, https://doi.org/10.1016/j.conbuildmat.2010.03.007

[25] Stellacci, S., Rato, V. and Polletti, E. (2016), "Structural permanence in pre- and post- earthquake Lisbon: half-timbered walls in overhanging dwellings and in pombalino

buildings”, *International Journal of Architectural Heritage*, Vol. 11 No. 3, pp. 363-381. 10.1080/15583058.2016.1233297

[26] Soares, P.M., Lima, D.C. and Miranda, P.M. (2019), “Mean and extreme temperatures in a warming climate: EURO CORDEX and WRF regional climate high-resolution projections for Portugal”, Climate Dynamics, Springer Science and Business Media LLC, Vol. 52 pp. 129-157.

[27] Li, J., & Chen, H. (2021). Optimization and Prediction of Design Variables Driven by Building Energy Performance - A Case Study of Office Building in Wuhan. The 2nd International Conference on Computational Design and Robotic Fabrication (CDRF 2020) (pp. 229-242). Shanghai: Springer.

[28] Zhang, H., Arens, E., & Pasut, W. (2011). Air temperature thresholds for indoor comfort and perceived air quality. Building Research & Information, 39, pp. 134-144.